Far Ultraviolet Spectral Analysis of the Prototype Nova-Like Variable VY Sculptoris from the High State to the Low State

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ABSTRACT

The prototype nova-like variable VY Sculptoris was observed by the IUE during four different optical brightness states of the system. The FUV flux level from the highest state to the lowest state declines by a factor of 28. We have carried out model accretion disk and white dwarf atmosphere fitting to the spectra. The corresponding accretion rates range from $\dot{M} = 8 \times 10^{-9} \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ at the highest FUV flux level down to $\dot{M} = 1.9 \times 10^{-10} \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ at the lowest flux level. We report tentative evidence for the detection of the underlying white dwarf with $T_{\mathrm{eff}} = 45,000$K in the spectrum with the lowest flux level.

Subject Headings: keywordStars Stars: cataclysmic variables, white dwarfs, Physical Processes: accretion, accretion disks

1. Introduction

Cataclysmic variables (CVs) are short-period binaries in which a late-type, Roche-lobe-filling main-sequence dwarf transfers gas through an accretion disk onto a rotating, accretion-heated white dwarf (WD). The nova-like variables are a subclass of CVs in which the mass-transfer rate is high and the light of the system is dominated by a very bright accretion disk. The spectra of nova-like variables resemble those of classical novae (CNe) that have settled back to quiescence. However, nova-like variables have never had a recorded CN outburst. Hence their evolutionary status is a mystery. They could be close to having their next CN explosion, or they may have had an unrecorded explosion, possibly hundreds or thousands of years ago. Adding to the mystery of nova-like variables is that some of them (known as

the VY Sculptoris stars after their prototype) show the curious behavior of being in a high optical brightness state most of the time, but then, for no apparent reason, plummeting into a deep low-brightness state with little or no ongoing accretion. Then, just as unpredictably, they return to the high-brightness state. These drops are possibly related to cessation of mass transfer from the K-M dwarf secondary star either by starspots positioned under L_1 (Livio and Pringle 1994) or irradiation feedback in which an inflated outer disk can modulate the mass transfer from the secondary by blocking irradiation of the hot inner accretion disk region(Wu et al. 1995).

VY Scl's brightest state has V = 12.9 and its low state has V = 18.5 (Warner 1987). Its orbital period is 0.1662 days but little else is known (Hollander, A., Kraakman, H., van Paradijs, J.1993 and references therein). Martinez-Pais et al (2000) found the white dwarf mass to be $M_{(wd)} = 1.22 \pm 0.22 M_{\odot}$, the mass of the secondary $M_{(2)} = 0.43 \pm 0.13 M_{\odot}$ and the binary inclination $i = 30^o \pm 10$ In its low state, VY Scl shows emission lines similar to dwarf novae in quiescence (Szkody 1987). A reddening correction of E(B-V) = 0.06 is given by Bruch and Engle (1995). Unfortunately, the distance is unknown.

During the low states of VY Scl stars, it is possible to obtain nearly uncontaminated spectra of the WD component because the accretion disk is very faint and cool if present at all. Thus, through model-atmosphere fitting during the low states, it is possible to determine temperatures, gravities, and abundances for the WD. This paper reports an analysis of FUV archival spectra which sample several different brightness states of the prototype, VY Scl itself. Among the key questions we seek to answer are the following: What are the accretion rates during outburst and quiescence? Is this rate of accretion consistent with the suppression of the disk instability mechanism? How much flux does the white dwarf contribute to the FUV? How much flux does the accretion disk contribute to the FUV? How hot is the white dwarf?

2. Far Ultraviolet Spectroscopic Observations

Far ultraviolet spectra of VY Scl were obtained over a period of four years with the International Ultraviolet Explorer Spacecraft short wavelength prime camera (SWP) through the large aperture at low dispersion with a resolution of 5Å. The SWP spectra covered the wavelength range 1170 Å - 2000 Å. Fortuitously, the series of observations included four spectra, SWP32594, SWP29755, SWP06123 and SWP21523, which covered a variety of brightness states from the optical high brightness state when the system was most luminous to intermediate brightness states down the low optical brightness state when, in VY Scl nova-like variables, the underlying white dwarf is thought to be exposed and the accretion

disk had greatly declined in brightness or gone away altogether. Due to large gaps in the AAVSO observations archive for VY Scl, we cannot display the placement of the observations on a light curve. However, the AAVSO data do indicate that at the time that SWP21523 was taken, the system was in a deep low state with V ¡ 15.8. Surprisingly, only one of the spectra, SWP32594, has been discussed in the literature (LaDous 1991; Hoare and Drew 1993). In Table 1, an observing log of the IUE archival spectra is presented in which by column: (1) lists the SWP spectrum number, (2) the aperture diameter, (3) the exposure time in seconds, (4) the date and time of the observation, (5) the continuum to background counts, and (6) the brightness state of the system.

The archival IUE NEWSIPS spectra were flux calibration-corrected using the algorithm of Massa and Fitzpatrick (2000). Massa and Fitzpatrick (2000) have shown that the absolute flux calibration of the NEWSIPS low dispersion data was inconsistent with its reference model and subject to time-dependent systematic effects, which together, amount to as much as 10-15%. Therefore, in order to correct the data and optimize the signal-to-noise, we used the IDL programs which apply Massa-Fitzpatrick corrections to VY Scl's low dispersion IUE data.

The reddening of VY Scl was determined based upon all estimates listed in the literature. The three principal sources of reddening values are the compilations of la Dous (1991), Verbunt (1987) and Bruch & Engel (1999). The compilation of Bruch & Engel listed E(B-V) = 0.06 for VY Scl. Therefore the spectra were de-reddened with this color excess using the IUERDAF routine UNRED. The brightness states of VY Scl at the time of the IUE observations were assessed by comparison with the AAVSO light curve data (visual magnitude versus Julian Date).

In figure 1, we display the four spectra together on the same flux scale. The spectrum with highest flux level (the top spectrum), SWP32594 is followed successively downward by two spectra of intermediate brightness and finally the bottom-most spectrum taken during

Table 1. IUE Observing Log

SWP	t_{exp}	Disp.	Ap.	Date of Observation		$F(\lambda 1350)$	C	B	State
32594	2100	LOW	Lg	1987-12-23	12:51:00	5.5×10^{-13}	144	20	High State
29755	420	LOW	Lg	1986-11-26	14:44:00	3.5×10^{-13}	41	17	High State
06123	2700	LOW	Lg	1979-08-09	01:02:00	1.7×10^{-13}	196	24	Intermediate
21523	7200	LOW	Lg	1983-11-12	15:01:00	2.0×10^{-14}	65	30	Deep Low State

a low state of VY Scl.

The outburst spectrum is dominated by absorption lines including P Cygni profile structure at C IV 1550, blue-shifted absorption at Si IV and absorption features due to C II 1335, Si II 1260, and N IV 1718. In SWP29755, the flux level has fallen to 3.5×10^{-13} and the absorption lines have weakened although N V 1240 and Si IV 1400 remain prominent. In spectrum SWP06123, C IV emission is seen but, in general, there is little convincing evidence for any other absorption features and the flux at 1350Å has declined to 1.7×10^{-13}. In the low state spectrum, SWP21523, all regions where absorption appeared in outburst and intermediate spectra have been replaced by emission lines and there is an underlying continuum. The strongest such emission lines are Si IV (1400) and C IV (1550).

3. Synthetic Spectral Fitting

We adopted model accretion disks from the optically thick disk model grid of Wade & Hubeny (1998). In these accretion disk models, the innermost disk radius, R_{in}, is fixed at a fractional white dwarf radius of $x = R_{in}/R_{wd} = 1.05$. The outermost disk radius, R_{out}, was chosen so that $T_{eff}(R_{out})$ is near 10,000K since disk annuli beyond this point, which are cooler zones with larger radii, would provide only a very small contribution to the mid and far UV disk flux, particularly the SWP FUV bandpass. The mass transfer rate is assumed to be the same for all radii. Thus, the run of disk temperature with radius is taken to be:

$$T_{eff}(r) = T_s x^{-3/4}(1 - x^{-1/2})^{1/4} \tag{1}$$

where $x = r/R_{wd}$ and $\sigma T_s^4 = 3GM_{wd}\dot{M}/8\pi R_{wd}^3$

Limb darkening of the disk is fully taken into account in the manner described by Diaz et al. (1996) involving the Eddington-Barbier relation, the increase of kinetic temperature with depth in the disk, and the wavelength and temperature dependence of the Planck function. The boundary layer contribution to the model flux is not included. However, the boundary layer is expected to contribute primarily in the extreme ultraviolet below the Lyman limit.

Model spectra with solar abundances were created for high gravity stellar atmospheres using TLUSTY (Hubeny 1988) and SYNSPEC (Hubeny & Lanz 1995). Using IUEFIT, a χ^2 minimization routine, both χ^2 values and a scale factor were computed for each model. The scale factor, normalized to a kiloparsec, can be related to the white dwarf radius through: $F_{\lambda(obs)} = 4pi(R^2/d^2)H_{\lambda(model)}$.

After masking emission lines in the spectra, we determined separately for each spectrum,

the best-fitting white dwarf-only models and the best-fitting disk-only models using IUEFIT, a χ^2 minimization routine. A dense grid of model spectra with solar abundances was created for high gravity stellar atmospheres using TLUSTY (Hubeny 1988) and SYNSPEC (Hubeny & Lanz 1995). We took a range of gravities in the fitting from Log $g = 7.0 - 9.0$ in steps of 0.5. For the white dwarf radii, we use the mass-radius relation from the evolutionary model grid of Matt Wood (private communication) for C-O cores.

Taking the best-fitting white dwarf model and combining it with the best-fitting disk model, we varied the accretion rate of the best-fitting disk model by a small multiplicative factor in the range 0.1 to 10 using a χ^2 minimization routine called DISKFIT. Using this method the best-fitting composite white dwarf plus disk model is determined based upon the minimum χ^2 value achieved and consistency of the scale factor-derived distance with the adopted distance for each system. The scale factor, S, normalized to a kiloparsec and solar radius, can be related to the white dwarf radius R through: $F_{\lambda(obs)} = SH_{\lambda(model)}$, where $S = 4\pi R^2 d^{-2}$, and d is the distance to the source.

The results of our fitting are summarized as follows. The spectra with the three highest flux levels are all dominated by an accretion disk. The best fitting disk models to SWP32594, SWP29755 and SWP06123 are displayed in figures 2, 3, and 4. In each case the accretion disk provides essentially all of the FUV flux even as the flux level at its peak in SWP32594 is lower by a factor of 3 in SWP06123.

In figure 2, the best-fitting disk model to SWP32594 corresponded to the following parameters: accretion rate $\dot{M} = 8 \times 10^{-9}M_\odot$ yr^{-1}, $M_{(wd)}$ =1.0M$_\odot$, and an inclination of 41^o with a $\chi^2 = 5.96$ The scale factor of this best fit yields a distance to VY Scl of 620 parsecs.

At the lower flux level of SWP29755, the best-fitting disk model is displayed in figure 3. This fit corresponded to the following parameters: accretion rate $\dot{M} = 5 \times 10^{-9}M_\odot$ yr^{-1}, $M_{(wd)}$ =1.0M$_\odot$, inclination of 41^o with a $\chi^2 = 7.86$. The scale factor of this fit yielded a distance of 616 pc.

The best-fitting disk model to SWP06123 corresponded to the following parameters: accretion rate $\dot{M} = 1.6 \times 10^{-9}M_\odot$ yr^{-1}, $M_{(wd)}$ =1.0M$_\odot$, and an inclination of 41^o with $\chi^2 =$ 5.74. The scale factor S yielded a distance to VY Scl of 536 parsecs. This fit is seen in figure 4

The spectrum with the lowest flux level, SWP21523 was obtained during a low state of VY Scl. The flux level at 1350A is lower by a factor of 28 than the spectrum in Figure 1 with the highest flux level. This spectrum contains a very significant contribution (34% of the flux) from a a hot WD but with the flux of an accretion disk still accounting for the majority (66%) of the FUV flux. If this spectrum recorded the deepest low state of VY Scl, then the

presence of a strong disk component is a departure from the totally white dwarf-dominated low state spectra of the low state nova-like systems MV Lyra, TT Ari and DW UMa. Our best-fitting white dwarf plus accretion disk combination fit to SWP21523 consisted of a hot solar composition WD with $T_{\rm eff} = 45,000{\rm K}\pm 3000K$, log$g = 8.5$ with a $\chi^2 = 3.38$ and accretion disk model with accretion rate $\dot{M} = 1.9 \times 10^{-10}{\rm M}_\odot$ yr^{-1}, $M_{(wd)}$ =1.0M$_\odot$, and an inclination of 41^o with $\chi^2 = 3.38$. The scale factor S yielded a distance to VY Scl of 536 parsecs. This fit is seen in figure 5.

It is important to explore the uncertainties in our estimated accretion rates, $\dot{M}$. In order to assess the errors in $\dot{M}$ through a formal error analysis, it is necessary to know the errors in the individual input parameters used to determine $\dot{M}$. These inexact parameters are the white dwarf mass, the orbital inclination, the distance to the system and the reddening. Each would produce errors in $\dot{M}$ and each parameter has its own uncertainties. Since each of these parameters affects either the continuum slope or the flux level or both, they affect the accretion rate. For example, Puebla et al. (2007) using similar disk models as ours but with a more sophisticated four dimensional multiparameter optimization fitting method, cite an error in E(B-V) of 0.02 to 0.05 producing errors in $\dot{M}$ of 30 to 50%. For a sense of the uncertainty of the accretion disk fitting method used in this paper, the reader is referred to Winter and Sion (2003) who carried out a formal error analysis with error contours for $\dot{M}$.

4. Conclusions

Our multi-component white dwarf photosphere plus accretion disk model analysis of the archival IUE spectra of VY Scl covered four different optical brightness states of the system. We find strong evidence that the accretion rate has declined from $\dot{M} = 8 \times 10^{-9}{\rm M}_\odot$ yr^{-1} at the highest FUV flux level down to $\dot{M} = 1.9 \times 10^{-10}{\rm M}_\odot$ yr^{-1} during the lowest brightness state spectroscopically recorded by the IUE. During this latter state of lowest flux, the white dwarf contributes substantially to the FUV flux. This is not unexpected for a nova-like low state since the underlying white dwarfs in the nova-like systems TT Ari (Gaensicke et al. 2001), MV Lyr (Linnell et al.2005), DW UMa (Knigge et al.2005) and V794 Aql (Godon et al.2007) are also exposed. The temperature estimate of 45,000K we obtain for the white dwarf in VY Scl must be regarded as preliminary. It is however interesting that the temperature for the WD in VY Scl is within the range of white dwarf temperatures measured for the other nova-like systems as seen in Table 2.

Since dwarf nova behavior is not seen in VY Scl-type and UX UMa-type nova-like variables, it is widely held that the supression of the disk instability mechanism requires that the accretion rate be higher than the critical mass transfer rate for dwarf nova outbursts.

This threshhold value as a function of white dwarf mass and orbital period is discussed in detail by Shafter, Wheeler and Cannizzo (1986). Referring to Figure 2 in Shafter et al.(1986), the accretion rates we estimated for VY Scl in its high states lie above the dwarf nova instability line for white dwarf masses from 0.4 to 1.0 Msun.

It is clear that higher quality FUV spectra are required to confirm the tentative results herein for VY Scl. Moreover, given the small size of the sample of exposed white dwarfs in nova-like systems, it is particularly important to catch more nova-like systems in their low states for both ground-based optical and space observations.

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Figure Captions

Fig. 1.— The four IUE spectra corresponding to four different brightness states from the peak of outburst (top spectrum, highest flux level) down to a deep low state (bottom spectrum, lowest flux level). Note the transition of the line spectrum as a function of brightness state from the outburst spectrum where absorption lines dominate down to the low state FUV spectrum when emission lines dominate the spectrum.

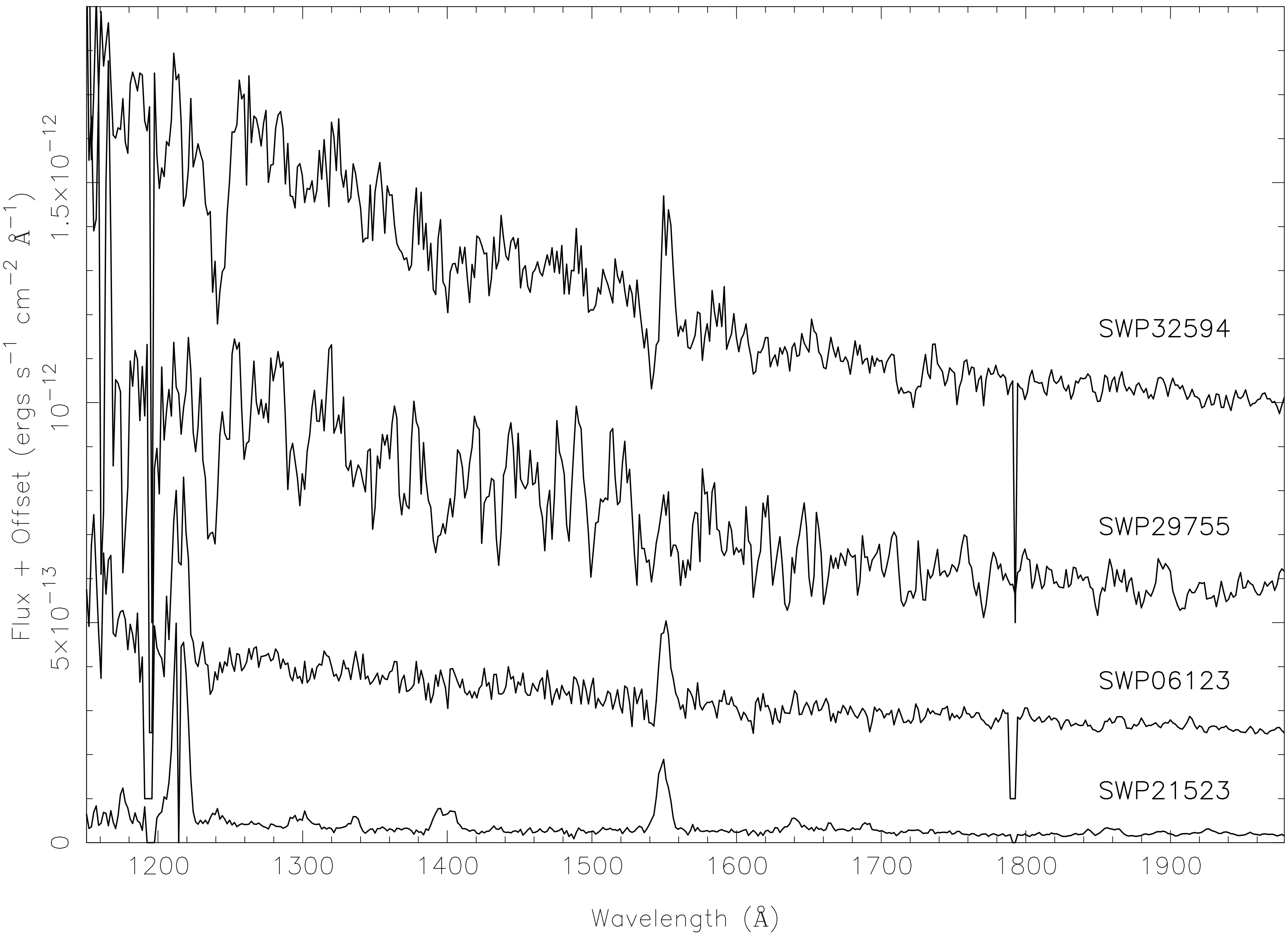
Fig. 2.— The best-fit accretion disk synthetic fluxes to the spectrum SWP32594 of VY Scl during its high state. The accretion disk corresponds to $\dot{M} = 8 \times 10^{-9} M_{\odot}$/yr, $i = 41^o$, and M$_{wd} = 1.0 M_{\odot}$. The top solid curve is the best-fitting combination, the dotted curve is the negligible contribution of the white dwarf alone and the dashed curve is the accretion disk

synthetic spectrum alone. In this fit, the white dwarf the accretion disk contributes 98% of the far UV flux and the white dwarf 2% of the flux.

Fig. 3.— The best-fit accretion disk synthetic fluxes to the spectrum SWP29755 of VY Scl during its high state. The accretion disk corresponds to $\dot{M} = 5 \times 10^{-9} M_{\odot}$/yr, $i = 41^o$, and $M_{wd} = 1.0 M_{\odot}$. The top solid curve is the best-fitting combination, the dotted curve is the contribution of the white dwarf alone and the dashed curve is the accretion disk synthetic spectrum alone. In this fit, the white dwarf the accretion disk contributes 98% of the far UV flux and the white dwarf 2% of the flux.

Fig. 4.— The best-fit accretion disk synthetic fluxes to the spectrum SWP of VY Scl during its high state. The accretion disk corresponds to $\dot{M} = 1.6 \times 10^{-9} M_{\odot}$/yr, $i = 41^o$, and $M_{wd} = 1.0 M_{\odot}$. The top solid curve is the best-fitting combination, the dotted curve is the small contribution of the white dwarf alone and the dashed curve is the accretion disk synthetic spectrum alone. In this fit, the white dwarf the accretion disk contributes 92% of the far UV flux and the white dwarf 8% of the flux.

Fig. 5.— The best-fit combination of white dwarf plus accretion disk synthetic fluxes to the spectrum of VY Scl during its low state. The white dwarf model has $T_{\rm eff} = 45,000$K, log $g = 8.5$ and the accretion disk corresponds to $\dot{M} = 1.9 \times 10^{-10} M_{\odot}$/yr, $i = 41^o$, and $M_{wd} = 1.0 M_{\odot}$. The top solid curve is the best-fitting combination, the dotted curve is the white dwarf spectrum alone and the dashed curve is the accretion disk synthetic spectrum alone. In this fit, the accretion disk contributes 66% of the far UV flux and the white dwarf 34% of the flux.


SWP32594
SWP29755
SWP06123
SWP21523
Flux + Offset (ergs s^{-1} cm^{-2} Å^{-1})
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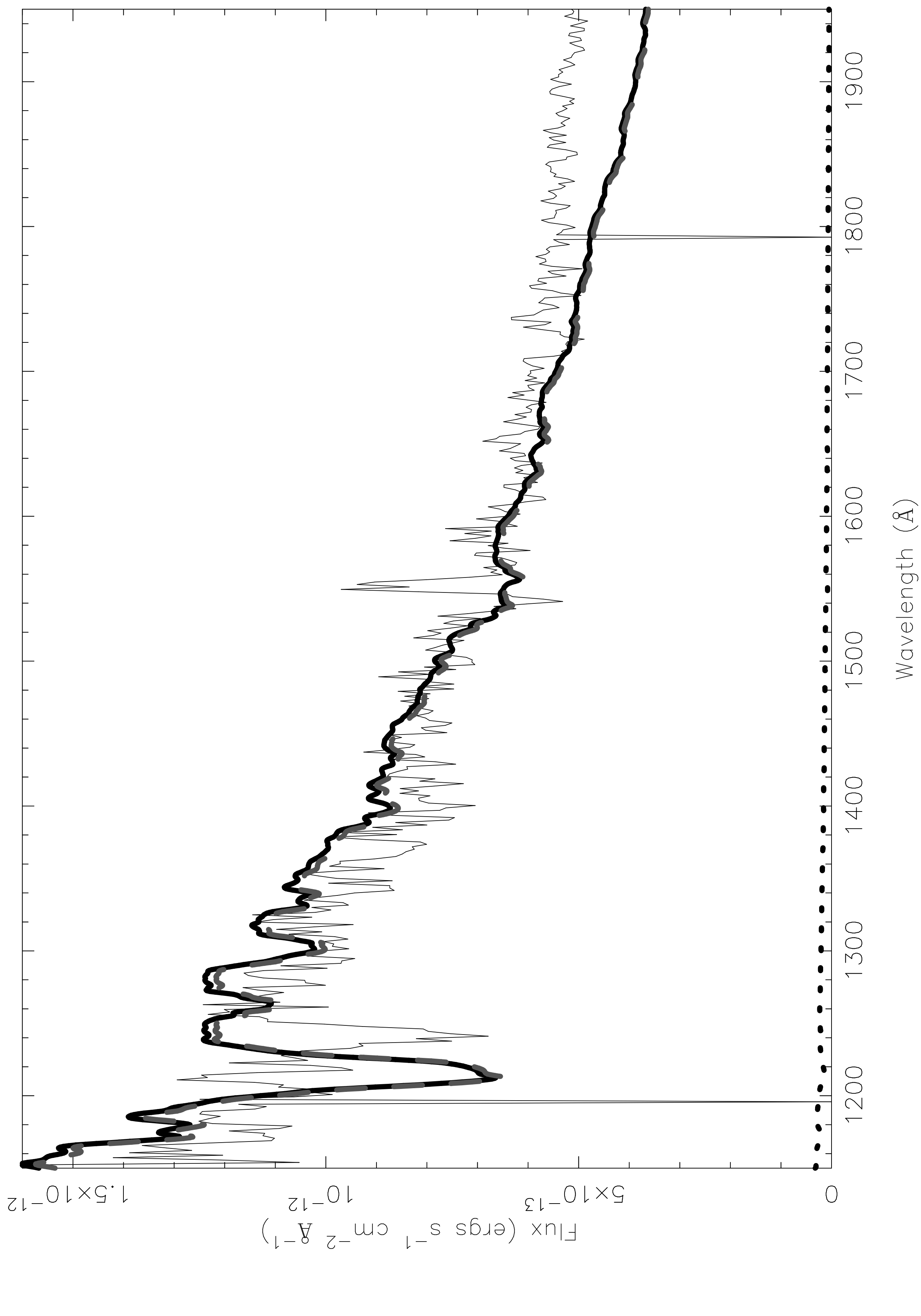
10^{-12}
5×10^{-13}
0
1200
1300
1400
1500
1600
1700
1800
1900
Wavelength (Å)



Flux (ergs s⁻¹ cm⁻² Å⁻¹)
0
5×10⁻¹³
10⁻¹²
1.5×10⁻¹²
Wavelength (Å)
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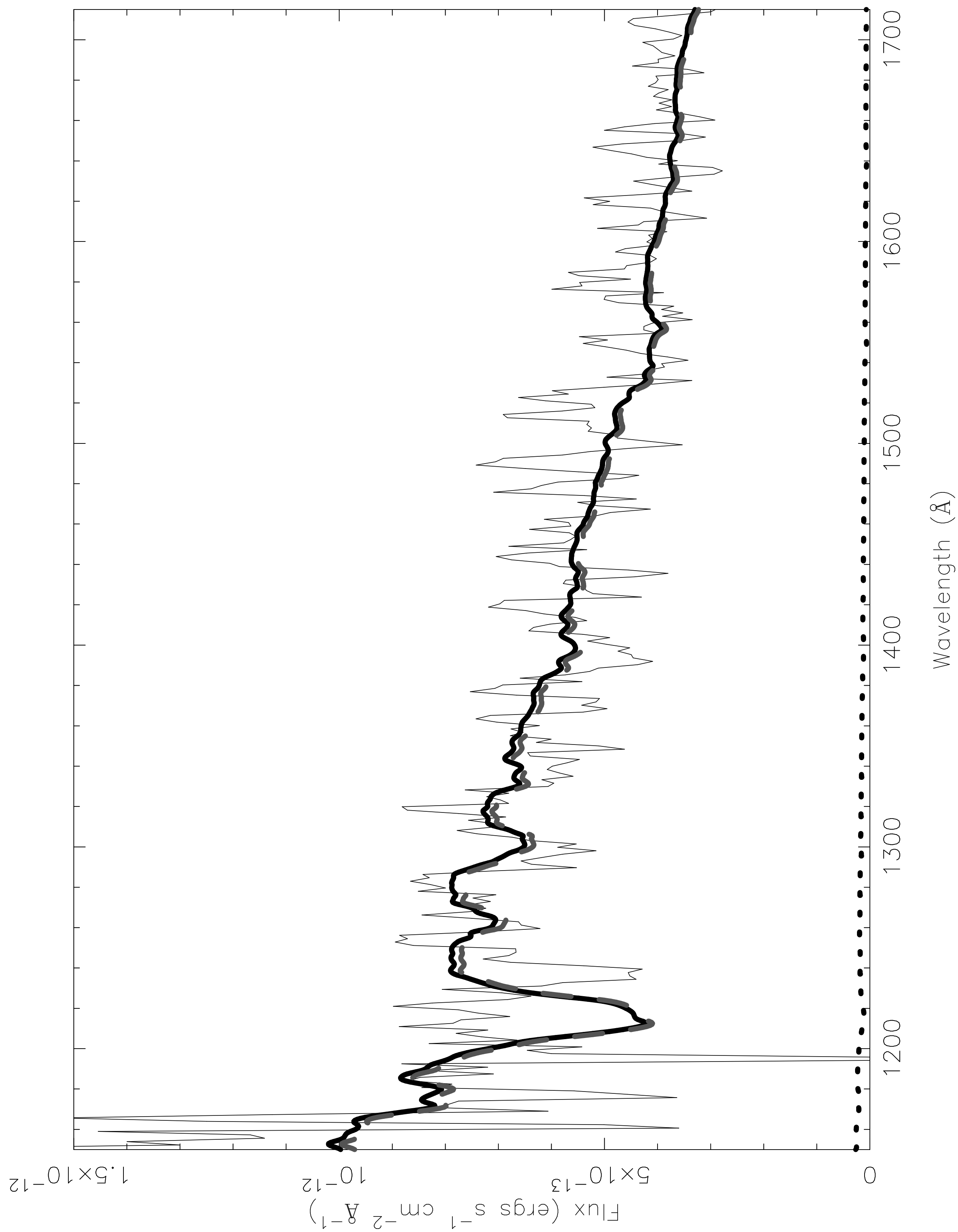
1500
1600
1700
1800
1900


Flux (ergs s⁻¹ cm⁻² Å⁻¹)
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Wavelength (Å)
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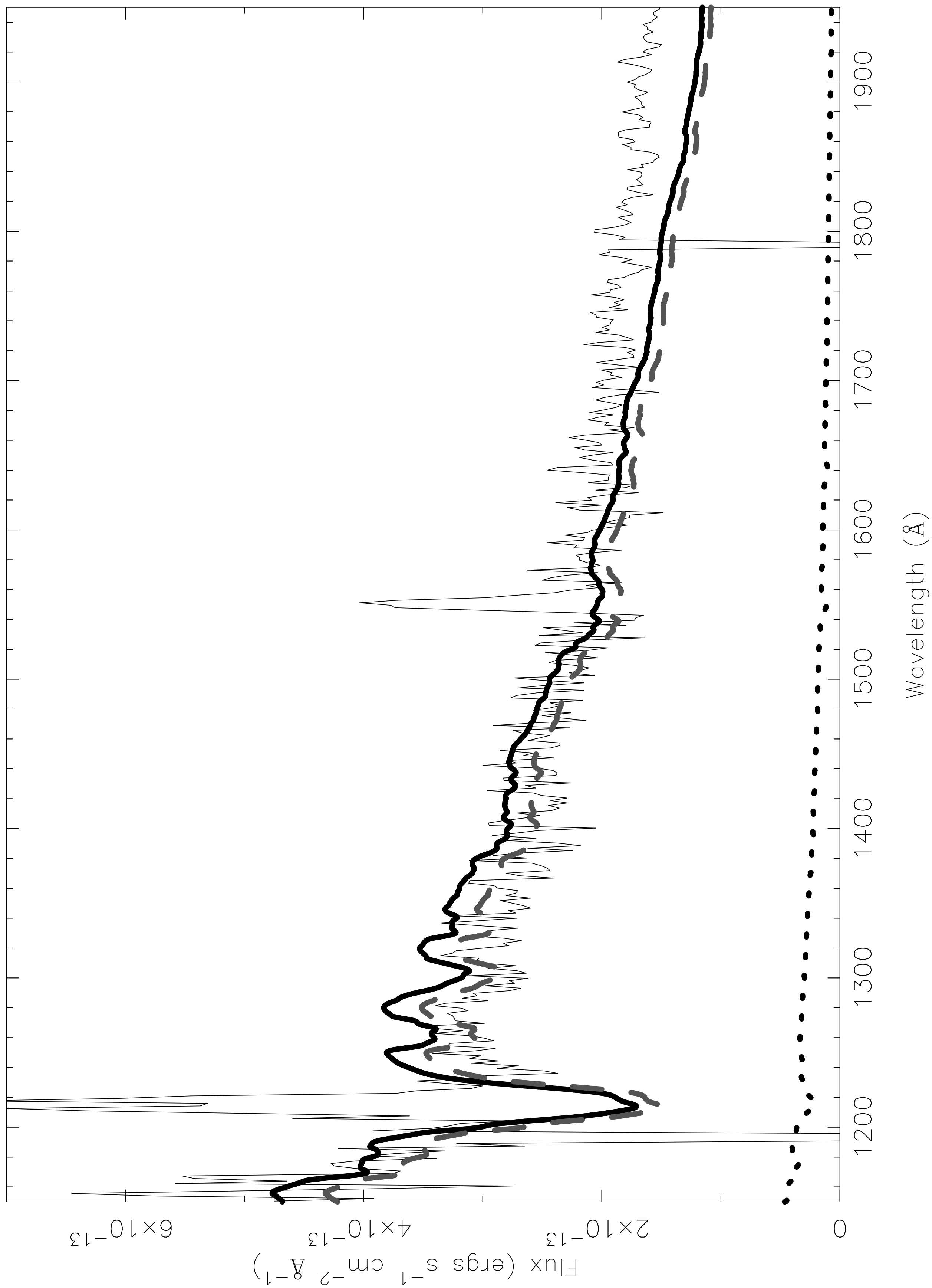
1400
1500
1600
1700



Wavelength (Å)
1200
1300
1400
1500
1600
1700
1800
1900
Flux (ergs s^{-1} cm^{-2} Å^{-1})
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2×10^{-13}
4×10^{-13}
6×10^{-13}

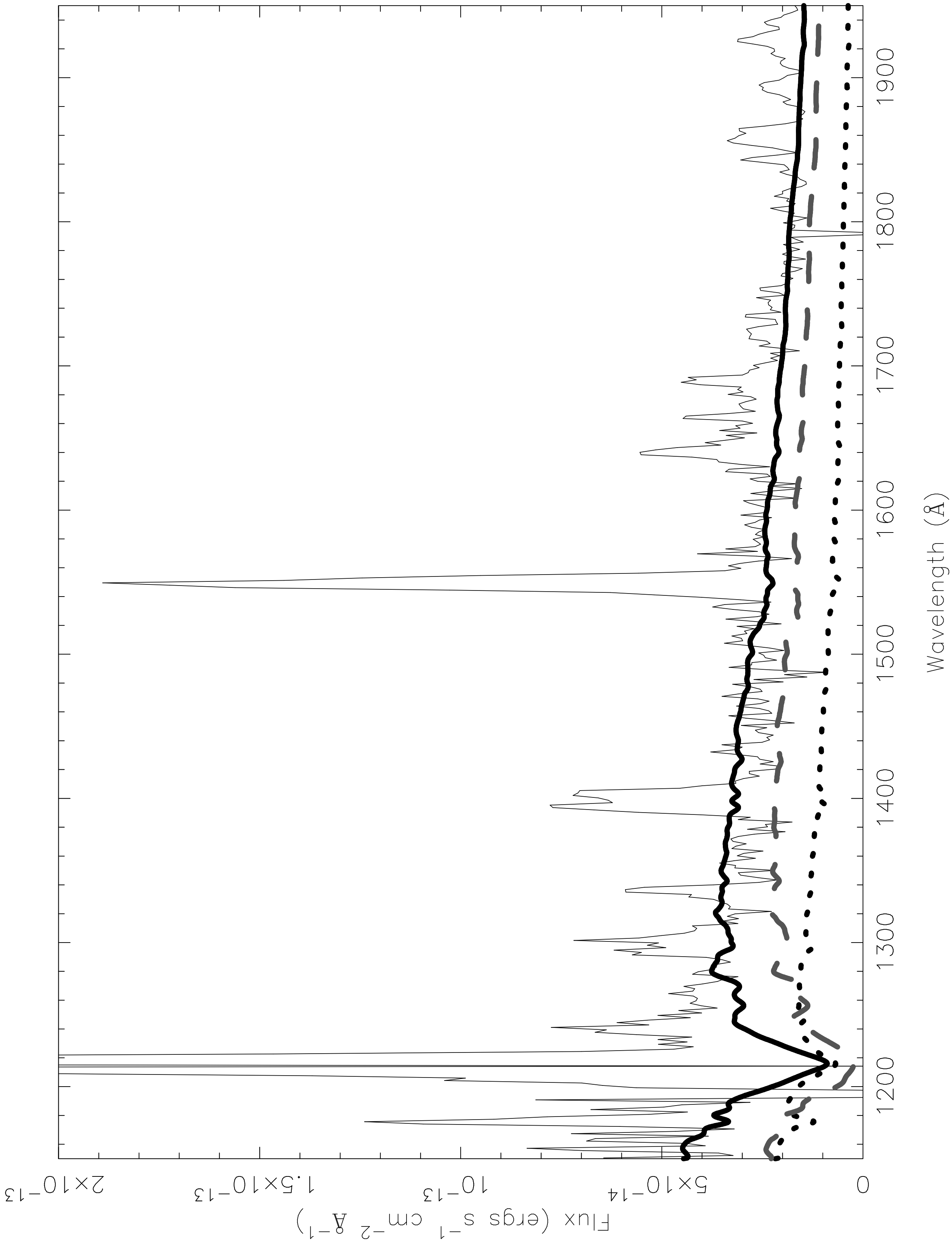
Wavelength (Å)
1200
1300
1400
1500
1600
1700
1800
1900
Flux (ergs s^{-1} cm^{-2} Å^{-1})
0
5×10^{-14}
10^{-13}
1.5×10^{-13}
2×10^{-13}

Table 2. Temperatures of WDs in VY Sculptoris-Type Nova-like Variables

Star	P_{orb}	d(pc)	Te
V794 Aql	0.2323	250	¿ 47,000 K
TT Ari	0.1375	185	40,000 K
MV Lyr	0.1329	335	47,000 K
DW UMa	0.1375	830	46,000K
VY Scl	0.1662	300	45,000 K

References: V794 Aql: Godon et al. (2007), ApJ, in press; TT Ari: Gaensicke et al. (2001); MV Lyr: Linnell et al. (2005); VY Scl: This paper.